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Effects of extensive forest management on soil productivity

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Abstract

This paper focuses on the effects of extensive forest management on soil productivity, its capacity to produce plants. Forest productivity, the summation of the productivities of the individual landscape elements (stands) that comprise the forest, is the integration of soil productivity, climate, species composition and stocking, and stand history. Extensive forest management can be operationally defined by the monetary investment per unit area of land, or by the number of stand entries per rotation, or by a combination of those metrics. A stand entered once during a rotation, for harvest, is extensively managed while a stand that has been subjected to site preparation, planted with genetically improved stock, and thinned and fertilized is intensively managed. The distinction blurs between those extremes. Many reviews have summarized the effects of forest harvest, the major extensive management activity, on soil properties and hence on productivity. Rather than simply reiterating those reviews, I have framed the paper in a series of axioms (which all agree upon), corollaries (consequences to productivity that follow from the axioms and are also agreed upon), and postulates (proposed consequences that are subject to some uncertainty). It is axiomatic that forest management activities alter soil physical, chemical, and biological properties. Changes have been well-documented, although their intensity and duration varies among locations and associated soil and forest types. Consequences of the changes in soil physical properties are clearly corollaries, and include reduced productivity due to surface erosion, mass flow, soil compaction, and rutting and puddling. Although the negative consequences of roads and skid trails to stand-level productivity may be considered to be corollaries, extrapolations of those consequences to the landscape is less clear and should be considered to be postulates. Similarly, consequences of changes in soil chemical and biological properties due to forest management should be considered to be postulates; not fully tested. Although soil chemical and biological properties are changed by management, the duration of those changes and their influence on productivity are not clear. Forest ecosystems are dynamic and resilient. Assessment of the consequences of changes in properties should recognize that shifts in preferred species may not be equated with changes in soil productivity, and that short-term effects may not be indicative of longer-term effects. Both ethical and economic considerations demand good stewardship of our natural resources. Extensive forest management, if carried out with both wisdom and prudence, is not antithetical to good stewardship.

Keywords: Soil productivity; Forest harvest; Nutrient depletion; Soil physical properties

1. Preface

1.1. Introduction

My objective is to review the effects of extensive forest management activities on soils, centering on those activities that are most likely to influence inherent soil productivity, "(its) capacity to produce … plants" (Soil Science Society of America, 1997). I will also attempt to rank the relative significance of the effects. The focus of this paper is on *soil productivity* as opposed to *forest productivity*. That may seem to be a semantic nuance, but it is an important distinction. Forest productivity is an all-encompassing term that is the summation of the productivities, often measured in

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merchantable yield, of the individual landscape elements (stands) that comprise the forest. Those productivities, in turn, are an integration of the effects of environment including soil but also including climate, species composition and stocking, and stand history including such disturbances such as fire, logging, insects or disease. Extensive forest management can be operationally defined by the monetary investment per unit area of land, or by the number of stand entries per rotation, or by a combination of those metrics. A stand that has been entered once during a rotation for harvest is extensively managed, while a stand that has been subjected to site preparation, planted with genetically improved stock, and thinned and fertilized is intensively managed. The distinction between those extremes blurs, and there are notable exceptions such as multiple entries into hardwood stands for high-grading (Nyland, 1992), an example of extensive rather than intensive management. The factors that affect forest productivity are usually poorly understood or controlled in extensive management, and the potential productivity that could be achieved under more intensive management is similarly unknown. I therefore focus on understanding the effects of management on soil productivity, generally assessed at the stand level, as a more attainable goal. Because I ascribe to the belief that "the ecosystem concept was never intended to serve as a basis for . . . resource management" (Fitzsimmons, 1966), I will emphasize productivity and not other more amorphous goals of management. Harvesting and forest protection, especially from fire, are the major extensive forest management activities although limited site preparation and planting may also be carried out. Except where explicitly noted, "extensive management" and "harvesting" are treated nearly synonymously in this paper.

1.2. Significance of effects

All forest management activities affect soils, with effects ranging over a continuum from nearly none where the activity is minimal to large. To foster communication, a threshold should be established above which effects merit attention and below which further consideration is not justified. The magnitude of that threshold varies with the state of knowledge, and must include a recognition of uncertainty. Failure to identify thresholds inhibits communication to a wider audience and even among ourselves.

Criteria that can be used to identify significant effects include:

- *Severity of effect.* Some effects influence productivity to a much greater degree than others.
- *Spatial extent.* This varies considerably, ranging from site-specific effects to those affecting a soil type, watershed, physiographic region, or other geographic entity.
- *Certainty.*
- *Duration (irreversibility).* Duration can be very short-term — only a year or two; to long-term — one generation or rotation of trees; to irreversible.
- *Deviation from natural range.* This places the effect in a broader context. Altered properties that fall within the natural range of variation may be less significant than those that deviate greatly from that range (Fig. 1).
- *Biological and economic implications.* These are particularly important where effects are indirect. For example, loss of surface soil via erosion following harvest may have minor effects on forest productivity but may have profound effects on adjacent aquatic systems.

1.3. Approach

There are two kinds of effects of forest management on soils. The first, direct effect is an alteration of soil properties such as an increase in bulk density following passage of heavy equipment. Soil scientists generally agree on those direct effects; recognition of those alterations is literally axiomatic. The second effect of management on soils is indirect; a change in site productivity due to alteration of soil properties. Some of those secondary effects are obvious enough that they can be considered corollaries. Specific studies and personal and vicarious experience have led to this worldview. Conversely, some of the indirect effects of management on soils are not as clear, and those effects can be considered hypotheses or postulates. The distinction between axioms, corollaries, and postulates is often in the eye of the beholder, and depends on interpretation of both published reports and personal observations. Papers that support a position are evaluated differently than those in opposition.

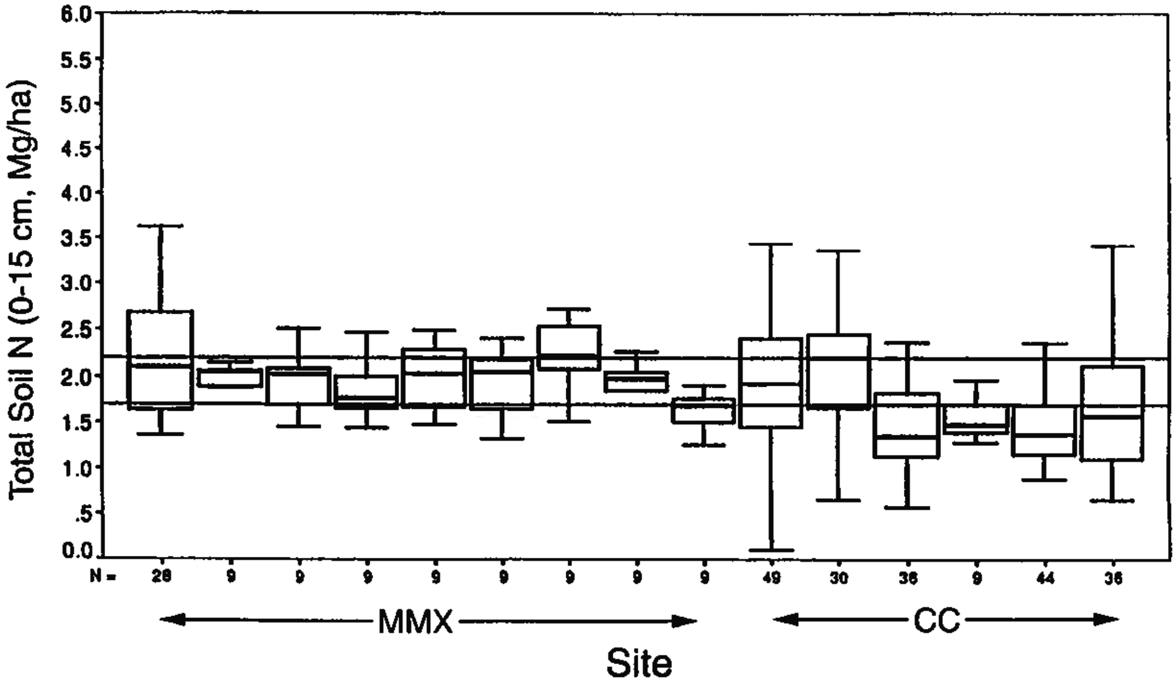

Fig. 1. Range of natural variability of soil N in upper 15 cm in mature mixedwood (MMX) and its change with forest harvesting in clearcut (CC) sites in Saskatchewan (Pennock and van Kessel, 1997).

I offer no excuses for bias; "For every expert, there is an equal and opposite expert" (Clarke, 1998).

To be comprehensive, I feel obligated to catalogue the major axioms and their corollaries. To do so, I have relied heavily on the numerous reviews of the effects of forest management on forest productivity as mediated through soils. Many of those reviews are cited directly, but others have been used to provide context. They include overall assessments (Stone, 1973; Leaf, 1979; Stone et al., 1979; Lousier and Still, 1988; Perry et al., 1989; Harvey and Neuenschwander, 1990; Grigal and Bates, 1992; Keenan and Kimmins, 1993), those directed at physical effects (Lull, 1959; Greacen and Sands, 1980; Froehlich and McNabb, 1984; Sidle et al., 1985; Groot, 1987; Standish et al., 1988), and those directed at nutrient-related effects (Federer et al., 1989; Brown and Binkley, 1994).

Based on a limited inquiry of peers, there are expected regional views of the effects of forest management on soils and productivity, such as the difference in concern about mass flow processes in the Pacific Northwest compared to the southeast Coastal Plain. Local or regional landforms, climates, vegetation, and forest management techniques produce a nearly infinite combination of problems or opportunities. To maintain a broad perspective, I will not address any regional subset in detail, but instead I will emphasize the unresolved questions; the postulates. The majority of those questions deal with effects of management on soil chemical and biological properties. The brevity of treatment of some of the axiom/corollary pairs is not indicative of their importance to forest sustainability, but of universal agreement. I will ultimately rank the relative importance of all effects.

2. Effects — erosion

Erosion is a natural process, but one whose rate and extent is exacerbated by forest management (Swanson et al., 1989). Most emphasis on erosion has been directed towards its effects on water quality and fish habitat, but because it involves displacement of soil, the growing medium, erosion also can affect site productivity (Megahan, 1990).

2.1. Changes — axioms

2.1.1. Surface erosion

Surface erosion is empirically related to topography, including slope length and steepness; rainfall amount, intensity and duration; soil properties such as infiltration rate; and vegetation and soil cover (Lowdermilk, 1930; Wischmeier and Smith, 1978; Dissmeyer and Foster, 1985; Elliot and Hall, 1997). In systems with erodible soils on steep slopes and with frequent and/or large storms, the potential for surface erosion is high. Management activities that expose the mineral soil by removing forest floor, decrease its infiltration capacity by compaction or by fire-induced hydrophobicity, remove natural debris dams such as coarse woody debris, and provide routes for accelerated water movement via roads and skid trails, all increase erosion compared to the natural system (Fig. 2).

2.1.2. Mass flow

Many landscapes are inherently unstable, and masses of soil material will move simultaneously downslope (Sidle et al., 1985). Natural factors that influence mass movement include geomorphology, soil properties, hydrology, vegetation, seismicity, and climatic variation, especially rainfall intensity and duration (Caine, 1980; Sidle et al., 1985). Activities such as road building and forest harvesting increase landscape instability and can lead to accelerated mass flow (Megahan, 1990).

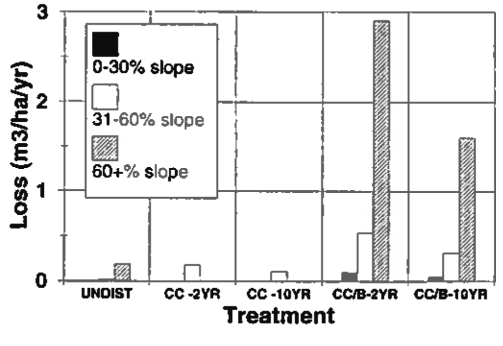

Fig. 2. Surface erosion by slope class and treatment, Willamette National Forest, Oregon. UNDIST: undisturbed forest; CC-2YR: clearcut, 2 years after treatment, no data for 60+% slope class; CC-10YR: clearcut, first decade after treatment, no data for 60+% slope class; CC/B-2YR: clearcut and burned, 2 years after treatment; CC/B-10YR: clearcut and burned, first decade after treatment. Data from Swanson et al. (1989).

2.2. Consequences — corollaries

2.2.1. Surface erosion

Surface erosion usually removes soil horizons that are superior for plant growth; the upper horizons that are high in organic matter and nutrients and low in bulk density. Both the nutrient capital and the water holding capacity of the soil are thereby diminished, and deeper horizons of lower quality become the rooting medium. Except in obvious cases such as gully erosion, diminishment of productivity due to surface erosion is difficult to quantify and is frequently associated with other soil changes such as compaction (Clayton et al., 1987). The potential increase in productivity in areas of sediment deposition also requires assessment so that net productivity changes at a landscape level can be ascertained. The loss of productivity with erosion has been quantified for agronomic soils with the productivity index (PI), which evaluates site productivity by the summation of the qualities of individual soil horizons (Larson et al., 1983; Pierce et al., 1983). That PI has also been applied to forest soils (Henderson et al., 1990; Gale et al., 1991), but only for assessing potential productivity on undisturbed sites. Use of the PI to evaluate changes in forest productivity with surface erosion, with windrowing or other site preparation techniques, or with compaction, remains to be explored.

2.2.2. Mass flow

Mass flow reduces forest production in both the area where the flow originates and in the receiving area. Although effects on productivity are severe (Smith et al., 1986), the disturbed areas are usually only a very small proportion of the landscape (Megahan et al., 1978; Jensen and Cole, 1965, cited in Megahan, 1990). Although such events can have major negative impacts on aquatic systems, they have recently been recognized as important for plant and animal diversity (Krajick, 1998).

3. Effects — soil physical properties

3.1. Changes — axioms

Abrupt changes in soil physical properties including structure, porosity, density, strength, pore size distribution, aeration, water retention, infiltrability, and hydraulic conductivity are consequences of forest management activities (Standish et al., 1988). Changes occur over a continuum of sites from constructed, heavy-duty roads where cut-and-fill has taken place (Megahan, 1988), to primary and secondary skid trails, and finally over the entire cut area, and the magnitude of change varies over a similar continuum.

3.1.1. Roads and landings

The proportion of area that is disturbed by constructed roads varies widely because of differences in topography, road specifications, and logging equipment (Megahan, 1988). As a result, summaries or central tendencies of reported data only provide a very general indication of the area that may be affected. Such summaries include those by Froehlich (1977) of 1.5–24% disturbed by roads, with an average "approaching 8%"; by Megahan (1988) of 1–30% roads and an added 1–10% in landings, with average total of about 10% for tractor and ground cable harvest and 2.5% for skyline and helicopter harvest; and by Grigal and Bates (1992) of 3–8%, with an overall average of 5.5%. In northern latitudes, winter roads on frozen ground including peatlands provide a low-cost and less disrupting alternative to constructed roads.

3.1.2. Compaction, puddling, and rutting

Soil compaction increases soil strength and reduces macropore space. Regardless of the equipment, a majority of compaction occurs during the first few passes (Reaves and Nichols, 1955; Froehlich and McNabb, 1984; Shepperd, 1993). If a soil is compacted, as opposed to reversibly compressed, a return to the initial, uncompacted state is very slow (Froehlich and McNabb, 1984) even in climates with freeze–thaw cycles (Corns, 1988; Shepperd, 1993; Stone and Elioff, 1998). In summary, "... the effects of soil compaction should be assumed to persist for several decades on forest sites" (Froehlich and McNabb, 1984, p. 179). Puddling, the reorientation of soil particles in response to an applied load, is most often associated with rutting. Both phenomena are most common on soils of low strength such as fine-textured mineral soils with high water contents (Moehring and Rawls, 1970) and peatlands (Groot, 1987).

3.2. Consequences

3.2.1. Roads — a postulate

The net effect of roads on productivity must be considered uncertain — a postulate. Roads have at least three effects on productivity. First, road construction is probably the single greatest contributor to surface erosion in the east (Patric, 1976), the south (Vowell, 1985), and in the west (Megahan, 1988), where it also leads to accelerated mass flow. Detrimental effects of erosion on productivity can then, in part, be directly attributed to roads. Although surface erosion associated with roads decreases rapidly following construction (Fig. 3), such detrimental effects can be considered corollaries.

Another effect of roads on productivity is the loss of area from the productive land base. Although this loss would seem to be directly proportional to the area of roads, and therefore also a corollary, reality is not as straightforward. First, some roads are closed following harvest and returned to the land base. Secondly, both the lack of competition and the moderately good rooting environment on fill portions of the road prism may lead to enhanced growth on that part of the area (Megahan, 1988). Finally, relative production may also increase on undisturbed areas adjacent to roads because of reduced competition for resources. The effect of winter roads on frozen ground is uncertain. At face value, their use would appear to have little effect on erosion, on soil properties, or even on productive

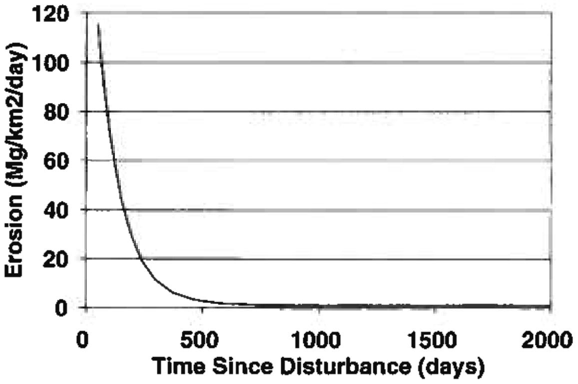

Fig. 3. Rate of erosion declining with time following construction of logging access roads in Deep Creek Study Area, Idaho Batholith. Material from entire road prism, including cut slopes and roadbed and fill slopes. Modified from Megahan (1974).

area. The kind of soil frost is important, however. The presence of deep, uniform frost with high bearing strength is seldom a universal certainty, and the degree to which conditions differ from that ideal influences the impact of winter roads.

The third and uncertain effect of roads is their disruption of hydrologic flow paths, both on steep slopes in mountainous areas (Megahan, 1988) and on nearly level wet sites such as peatlands (Stoeckeler, 1967; Boelter and Close, 1974). In both situations, this disruption increases water on the upslope side and reduces it downslope. Depending on the site and climate, this can lead to depressed growth either below roads in dry, steep terrain or upslope of roads in flat and wet terrain, and an enhancement of growth on the "other side" of the road. As with surface erosion, productivity changes associated with roads must be evaluated at a landscape level, and evaluations of net change have not been reported.

3.2.2. *Compaction, puddling and rutting — corollaries*

Compaction causes reduced tree growth because of reduced water permeability, restricted root space, and poor aeration. Although compaction is usually measured by change in bulk density (Meurisse, 1988), that neither fully measures the change in relative macropore/micropore distribution (Childs et al., 1989) nor soil strength (Stone and Elioff, 1998), both of which are important to tree growth (Greacen and Sands, 1980). The relative effect of change in bulk density on root growth also varies with soil texture (Daddow and Warrington, 1983). There is abundant evidence for a decrease in tree growth related to compaction, including that of conifer seedlings (Froehlich and McNabb, 1984), vegetatively reproduced sprouts (Shepperd, 1993; Stone and Elioff, 1998), and mature conifers in both the Pacific Northwest (Froehlich, 1976) and the Southeast (Moehring and Rawls, 1970).

Rutted areas are removed from the land base, and in some climates they remain filled with water, creating barriers to rooting. Rutting also channels surface runoff, leading to erosion, and this may be compounded by compaction or puddling in the base of the rut. Just as with roads, ruts can also disrupt drainage patterns, increasing water ponding in impermeable soils or wet systems such as bottomland hardwoods and peatlands. Although few studies have specifically investigated the direct effect of rutting on tree growth, Perry (1964) reported volume growth of loblolly pine within ruts was less than half of those planted outside of ruts in a 26-year-old plantation in North Carolina (Fig. 4).

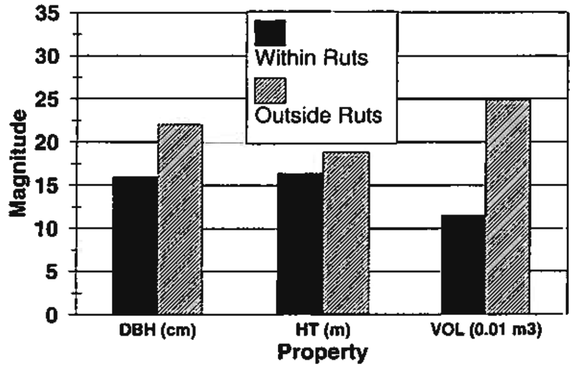

Fig. 4. Differences in growth of 26-year-old loblolly pine planted in ruts compared to those planted outside of ruts in North Carolina. Data, means of 30 trees of each treatment, are from Perry (1964).

4. Effects — disturbance, a collective measure

4.1. *Changes — axiom*

Many studies of the effects of harvesting on soil properties have measured the proportion of the area that is disturbed, but have not explicitly described it as compacted, rutted, puddled, or eroded. Common descriptors include undisturbed and three categories of disturbance: light disturbance, with shallow scarification; moderate disturbance, secondary skid trails or compaction and/or rutting up to 5–8 cm deep; heavy disturbance, primary skid trails, landings, or rutting at least 10–15 cm deep. Just as with roads, the proportion of area disturbed depends on such variables as equipment, terrain, and product. Summaries show disturbance to range from 3 to 62% (Froehlich, 1988), 1 to 36% (Megahan, 1980), 50 to 95% (Grigal and Bates, 1992), about 40% (Cromack et al., 1978), and 70 to 93% (Martin, 1988). Because these data are so variable and usually do not specify the kind of disturbance, they are difficult to interpret. There is no question, however, that they record a substantial alteration of soil properties over 25–50% of the harvest area.

4.2. Consequences — a corollary

As noted earlier, it is most meaningful to measure the net effect of forest management activities over an entire site or the landscape of many sites. Disturbance is usually measured over an entire site, and its effect on productivity is similarly integrated. Productivity losses associated with stand-level disturbance range from 14% for Douglas-fir (Smith and Wass, 1979), to 16% for ponderosa pine (Clayton et al., 1987), to 9% for thinning of Douglas-fir (Froehlich, 1976), to an overall range from 5 to 15% (Froehlich, 1988). In summary and loosely generalizing, there appears that about a 10% loss of productivity due to site disturbance.

5. Effects — soil chemical properties

5.1. Changes — axioms

Forest management activities directly and indirectly remove nutrients from a site, and the resulting effect on site quality has been a concern for more than two decades (Leaf, 1979). Whether this removal is deleterious to sustained productivity depends upon the initial nutrient capital of the system and on the balance between inputs via natural or artificial sources (i.e., fertilization) and losses via natural processes or increased by perturbations.

5.1.1. Increased runoff

Decreased evapotranspiration and resulting increased runoff are nearly universal consequences of forest harvesting. The result, as increased stream flow or deep leaching, inevitably leads to temporary increases in nutrient flux from harvested sites. Since the landmark study at Hubbard Brook (Bormann et al., 1968), concern has especially focused on losses of nitrogen (N), and to a lesser extent of phosphorus (P), from the terrestrial system. Careful reviews conducted both more than two decades ago (Stone, 1973) and much more recently (Brown and Binkley, 1994) have led to the same conclusion; significant changes in stream export of N following harvest have almost exclusively occurred in northern hardwood forests in the area of the White Mountains of New Hampshire, and significant losses of P are even rarer (Brown and Binkley, 1994). Over the remainder of the continent, studies have found relatively little change in stream chemistry following forest harvest. Although stream chemistry has changed little, effects on sediment load and fish habitat suitability have been demonstrated following harvest, especially associated with roads (Brown and Binkley, 1994), but those changes are outside the purview of this discussion.

5.1.2. Loss in product

Forest harvest unquestionably removes nutrients in the extracted products, and measurement of that removal and of the soil nutrient capital is straightforward. The amounts of nutrients that are removed vary with tree species and the amount and kind of product (i.e., bole only, bole plus bark, whole-tree, etc.), and soils similarly vary widely in nutrient capital. The resulting permutations and combinations have led to differing levels of concern regarding nutrient loss. Initiation of interest in whole-tree harvesting as a method to increase yields per unit land area (Keays, 1971) quickly led to studies of nutrient losses associated with different levels of utilization (Boyle and Ek, 1972; Weetman and Webber, 1972; Mälkönen, 1973; Kimmins and Krumlik, 1976; Nykvist, 1977). Although early concern was directed at losses of N, which was implicated in second-rotation decline in intensively managed stands in the Southern Hemisphere (Keeves, 1966; Whyte, 1973), most assessments dealing with extensive management agree that atmospheric deposition is sufficient to replace N and sulfur (S) removed via stem-only harvests of mature stands (Morris and Miller, 1994). Most of these assessments use a simple input–output budget to arrive at their conclusions, and the difference between total and available nutrient content and flux, especially for N, is a significant uncertainty (Rolff, 1988). If removed nutrients are disproportionally derived from available pools, then removals may be much more significant than usually indicated. The removal of nutrients associated with whole-tree harvesting, however, has led to continued concern, especially centered on macronutrients that are at low levels in atmospheric deposition, including P, K, and Ca. Of those, removal of P is proportionally the greatest when whole-tree harvest is compared to stemwood harvest in Finnish forests (Mälkönen, 1976). On shallow soils in Ontario, indications are that K losses from whole-tree harvest may not be replaced over a rotation (Morris, 1997), while on peatlands K and P are of similar concern (Grigal and Brooks, 1997; Teng et al., 1997). A large number of studies have implicated calcium (Ca) as the nutrient most likely to be depleted over time because removals apparently exceed natural replacement (summarized by Federer et al., 1989).

5.2. *Consequences — postulates*

In contrast to the general agreement on consequences of changes in soil physical properties to forest productivity, the consequences of changes in chemical properties can be considered to be postulates. Differences exist in interpretation of data.

5.2.1. *Increased runoff*

Nutrients losses in runoff following harvest do not appear to be important in affecting productivity. This postulate has two bases; the lack of replication of large losses except in the White Mountains (Brown and Binkley, 1994) and the relatively small absolute quantities of loss even in these extreme cases (Hornbeck et al., 1986). It is reasonable to assume that any effects of nutrient loss on productivity would be better demonstrated following the larger losses in the removed products.

5.2.2. *Loss in product*

The relevant question is whether nutrient removal by extensive forestry reduces long-term productivity. There is circumstantial evidence for such decreases, but most examples are unique. Diminished growth in Europe was associated with nutrient removal, but the removal usually included both multiple harvests of trees and collection of forest floor for use as animal bedding (Wiedemann, 1935; Baule and Fricker, 1970). Experimental removals of litter have led to relatively large growth reductions (30% less volume after 8 years, *Pinus sylvestris* L., — van Goor and Tiemens, 1963, Fig. 5) to lesser reductions (estimated 10% less increment of Scandinavian conifers — Lundkvist, 1988; 12% less volume after 16 years for *Pinus radiata* — Ballard and Will, 1981), but accompanied with measurable depletion of soil nutrient capital (Ballard and Will, 1981; Olsson et al., 1996). The evidence is circumstantial because it is not completely clear whether observed effects were due to removal of nutrients or other changes, such as alterations of water status. Other documented cases of nutrient removal affecting productivity have occurred in intensively managed forests, but conditions such as exotic species, high stockings, rapid growth and resulting short rotations, on sites that were often of initially low nutrient status and did not support native forests, make those cases of marginal relevance to the current issue. There are some reports of growth reductions linked to nutrient removal in less intensively managed forests, primarily associated with whole-tree harvest. For example, whole-tree harvest of Douglas-fir had a stronger effect on depression of 10-year height growth on poor sites than on better sites; and depression was ameliorated by N fertilization (Compton and Cole, 1991). It is likely that whole-tree harvesting, especially on poorer sites, will require fertilization to maintain productivity (Mälkönen, 1976).

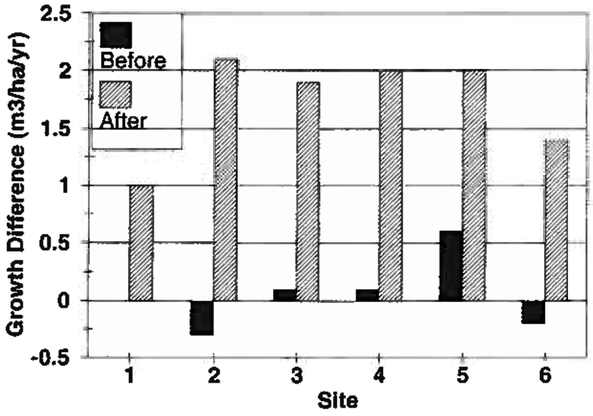

Fig. 5. Difference in average growth between six pairs of Scotch pine stands in the Netherlands for 8-year period before and after experimental removal of litter. Stands were about 45 years old, and averaged 7.5 m^3 ha^{-1} per year growth before treatment. Data from van Goor and Tiemens (1963).

The issue of Ca depletion, especially through interactions of acidic deposition and harvest, is a recurring theme (Federer et al., 1989; Hornbeck et al., 1990; Likens et al., 1996). Few studies have assessed long-term impacts of harvest on soil Ca; one to two decades are the longest periods reported. No statistically significant changes in soil Ca were detected for 8 years following whole-tree harvest of aspen in the Great Lakes States (Alban and Perala, 1990), 15 years after whole-tree harvest of mixed oak in Tennessee (Johnson and Todd, 1998), 17 years after a clearcut sawlog

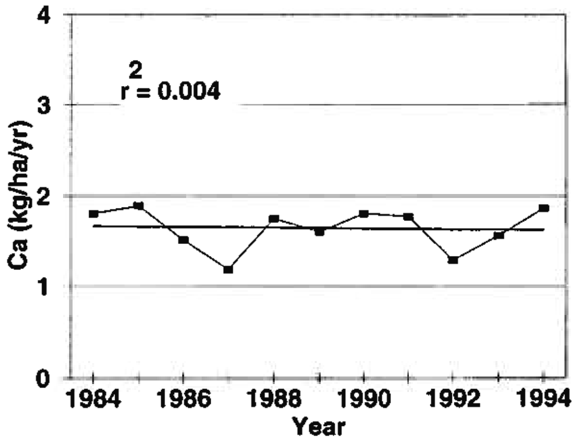

Fig. 6. Lack of change in Ca flux in precipitation over the past 10 years at six deposition monitoring stations in Minnesota.

harvest of hardwoods in the southern Appalachians (Knoepp and Swank, 1997), nor 8 years after clearcut harvest of northern hardwoods in New Hampshire (Johnson et al., 1997a). The balance between inputs and losses of available Ca are also uncertain. Studies of soil development demonstrate nearly universal loss of bases and decrease in pH with time (Bockheim, 1980). Although there is evidence for long-term declines in inputs of Ca in precipitation in the eastern US (Hedin et al., 1994), there is no such trend over the past 10 years in the mid-continent (Fig. 6). Additions of Ca via dry deposition (Johnson and Lindberg, 1992) and mineral weathering are also difficult to assess (Kolka et al., 1996). The forest cover type apparently influences both the rate of weathering (Homann et al., 1992) and the rate of leaching loss (Bockheim et al., 1984; Eriksson and Jönsson, 1994), and therefore affects the resulting levels of nutrients in both the soil and the vegetation (Wilson and Grigal, 1995). Other studies using both the retrospective approach (inferring effects of a treatment by comparison with apparently similar control areas — Kimmins, 1997) (e.g., Alban, 1982; Binkley and Valentine, 1991) and long-term monitoring (e.g., Johnson et al., 1988; Knoepp and Swank, 1994) have attributed declines in soil Ca and other cations at least in part to vegetation sequestration that exceeds natural rates of replacement.

Evidence for Ca deficiency in natural stands is limited and appears to be a consequence of acidic deposition and not harvesting (Schulze, 1989; McLaughlin et al., 1990; Shortle et al., 1997). Because of intensive study and reporting, excess Ca loss may appear to be prevalent but geographic representativeness beyond areas at high altitude with high levels of acidic deposition is unclear. Forests in the southwestern US have much higher fluxes of base cations, both inputs and outputs, than more humid eastern forests (Johnson et al., 1997b). Harvest removals of Ca are replaced by weathering in less than one rotation in the Idaho Batholith (Clayton and Kennedy, 1985). Although some reports have related soil Ca to tree productivity (Stoeckeler, 1960; Turvey and Smethurst, 1994), its covariance with many other soil properties make cause-and-effect difficult to determine (Turvey and Smethurst, 1994). Experimental manipulations of soil Ca are difficult because the most meaningful data would be from depletion studies, and soil pools are usually too large to appreciably alter. Manipulations of Ca also affect Ca–Al-pH interactions and markedly alter soil chemical status. In the southern Appalachians, Joslin and Wolfe (1994) increased foliar growth and Ca concentrations of red spruce by fertilization, but additions of Ca associated with liming have often reported a negative response (Derome et al., 1986; Andersson and Persson, 1988) usually attributed to altered soil chemistry due to the change in pH.

This discussion demonstrates the uncertainties associated with the effects of nutrient removal on productivity, even in the case of Ca where there appears to be some concern. These uncertainties confirm the status of the effects of nutrient removal on productivity as being a postulate, in need of further examination. Major issues requiring further work are the need to identify fragile sites at risk for nutrient loss (Weetman, 1998) and to understand the relationship between available nutrients and those removed in harvest.

6. Effects — soil biological properties

6.1. Changes — axioms

Forest management including harvesting and site preparation alters vascular plant communities, moving them towards an earlier successional stage by either or both changing the age–class distribution of the tree species and altering species composition. Similarly, at a minimum such activities alter both the substrate for soil organisms and their microclimate and therefore alter the composition of the soil biological community (Amaranthus et al., 1989).

Coarse woody debris (CWD) is often included under the topic of soil biological properties. Although the issue of forest management and CWD was first brought to the fore in the Pacific Northwest, it is now considered to be important everywhere (Harmon et al., 1986). Forest management clearly affects CWD; at the minimum harvesting removes its source. Forest management may further affect CWD by intentional or inadvertent felling of snags and by yarding or piling unmerchantable material (Franklin et al., 1989). Data from many regions indicates significant differences in CWD in previously harvested stands compared to old-growth stands, including differences in quantity and in distribution among size classes, degrees of decomposition, and structural position (Gore and Patterson, 1986; Sturtevant et al., 1997).

6.2. *Consequences — postulates*

Wilde (1958), in his textbook, differentiated forest soils from other soils on the basis of three criteria, including the difference in soil organisms, and more recent research has not altered that perception of the fundamental importance of soil organisms. They have roles in nutrient cycling including nitrogen fixation, protection against pathogens, development of soil structure, and enhancement of water availability to plants (Amaranthus et al., 1989). In order to maintain those functions, there is a strong feeling that both the range of individual groups of organisms and the diversity within groups must be retained as insurance against our ignorance of ecosystem processes (Franklin et al., 1989).

The best documentation of both the direct and the indirect effect of harvesting on soil organisms, with potential effects on productivity, is associated with mycorrhizae. The importance of mycorrhizae has been recognized for decades, but the positive results on reforestation and growth with manipulation of *Pisolithus tinctorius* in the Southeast (Marx and Krupa, 1978) have emphasized that importance. Forest management activities that lead to severe site disturbance such as intense fires, compaction, or loss of organic matter can alter mycorrhizal communities (Amaranthus et al., 1989). This has the potential to disrupt the spatial and temporal linkages of plants via mycorrhizae (Amaranthus and Perry, 1994; Simard et al., 1997) and may delay forest establishment for many decades (Perry et al., 1982), obviously having serious consequences to forest productivity.

In spite of this information, I consider the consequences of management-induced changes in soil biological properties (soil organisms) on productivity as postulates. In most cases where disruption of soil biological systems is suspected of affecting productivity, the system has also been altered in other ways so that direct cause-and-effect is difficult to determine (Perry et al., 1982). The fact that the soil biota change is not sufficient evidence that the change has affected productivity. A succession of fungal species accompany changes in soil characteristics, forest type, and forest age (Cline and Marx, 1995). Early stage mycorrhizae are adapted to open environments and competition for nutrients; second-stage mycorrhizae are associated with less temperature fluctuation, accumulating organic matter, and less nutrient demand from the host tree; third-stage forms occur in old-growth systems with N immobilization in humus leading to its potential deficiency (Cline and Marx, 1995). This successional development, in concert with the successional development of the forest overstory (Dighton and Mason, 1985), may lead to quite different populations of soil biota following harvest compared to adjacent unharvested sites. What is important is changes in productivity with changes in soil populations, not the changes in populations per se.

Forest biological systems are very resilient. The land-use history of New England has been well-documented. Regionally, only about 30% of the region was forested in 1850 compared to approximately 70% currently, with much of the current remainder in urban land (Foster, 1995). The modern and pre-settlement forest types are also regionally similar despite structural changes and the loss of some tree species (e.g., *Castanea dentata* through chestnut blight) (Foster, 1992). Within specific tracts of land some long-lasting effects remain, related to the interaction of site history, such as previous land-use and time of abandonment, and to site properties such as soil drainage (Foster, 1992; Motzkin et al., 1996). As a result, even though the present forest appears to be mature and stable, it is unlike previous forests (Foster et al., 1992). The same comment could probably be made, however, for nearly any disturbed or undisturbed forest in North America. In spite of profound changes in land-use and assumed contemporary changes in soil biological systems, substantial natural reforestation has taken place. In a case where effects on forest productivity of previous land-use was determined, there were no differences (Motzkin et al., 1996).

Although land-use changes have been best documented in New England, there are other examples of forest resilience in the US. The currently productive pineries in the south were once eroded cotton fields (Richter and Markewitz, 1996). The Great Lakes States of Minnesota, Michigan, and Wisconsin were almost wholly clearcut and burned, with virtually no attempt made to regenerate the forest. Yet all these lands now contain forests. Although such land stewardship should not be emulated, the resiliency of the forest and associated soil biological communities is impressive. There may be special cases, however, such as that cited earlier where conditions following harvest are so severe that essential symbiotic organisms are eliminated, seriously slowing tree re-establishment (Perry et al., 1982; Amaranthus et al., 1989). These cases must be evaluated in the context of the reversibility and duration. In some cases, forests may simply not be suited to the current environment and became established during other, more favorable periods. If societal goals demand forests in those locations, then their maintenance demands special (heroic?) measures.

The consequences of the effects of forest management on CWD are similarly subtle, and also fall into the realm of postulates. One of the concerns is that a reduction of CWD leads to the reduction of both habitats and substrate for soil organisms, with associated unknown consequences on productivity (Franklin et al., 1989). For example, loss of CWD by management can adversely affect non-symbiotic N fixation (Jurgensen et al., 1992). Reduction of CWD due to harvest is also postulated to ultimately reduce soil organic matter (SOM), with resulting effects on soil physical properties and nutrient and water retention and long-term productivity. As a result, management guidelines have been developed for CWD in some regions (Graham et al., 1994). Neither of these concerns, those associated with organisms and their functions nor those associated with SOM, have been rigorously tested; we have postulates, not corollaries.

Although changes in organisms and their functions are difficult to measure and even difficult to define, changes in SOM should be easier to measure. Differences in harvesting intensity and in the amount of CWD (slash) remaining on a site apparently had little effect on SOM after 15 years in the southeast US (Johnson and Todd, 1997) nor after 8 years in the north central US (Alban and Perala, 1990). In fact, a conclusion of the former study is that "... dead logs are an ephemeral and rather unimportant component of southeastern mixed oak forests..." (Johnson and Todd, 1997). Although often done, comparisons of CWD in harvested stands with that in old-growth stands is only marginally instructive; few studies have compared CWD in natural and managed stands over the entire sequence of stand development (Duvall, 1997). The CWD on a site following a natural disturbance such as a windstorm or a fire far exceeds that on a site following harvest, but how does CWD differ among managed and unmanaged stands at the same developmental stage? Both the trajectory of change over time and especially the importance of CWD to productivity are critical.

In contrast to the emphasis on increases in SOM in the system, there are clear cases of reductions in productivity associated with accumulation of SOM. One such case is the continual accumulation of forest floor and consequent low productivity in the taiga of Alaska (Van Cleve and Dyrness, 1983). Following disturbance, usually by fire, there is an increase in net primary production of vascular plants because of the increase in available nutrients. Over time (ca. 150 years), however, forest floor continues to accumulate via a positive feedback with low temperatures and reduced aeration, significantly reducing productivity (Van Cleve et al., 1983). Paludification of terrestrial sites along the northwest coast of North America occurs by a similar process and also leads to low productivity (Ugolini and Mann, 1979). Finally, ericaceous plants are associated with a unique and economically important case of continuous forest floor accumulation (de Montigny and Weetman, 1990). Effects are well-documented in England (Read, 1984), Newfoundland (Titus et al., 1995), western British Columbia (Weetman et al., 1990), and Fennoscandinavia (Nillson, 1994). A substantial "growth check" of the conifer tree species that are associated with the ericads occurs through both slowed mineralization of N and P and disruption of membranes of tree roots and associated mycorrhizae. In all these cases, forest harvesting may have a positive effect on productivity by enhancing decomposition, or negative effects by reducing evapotranspiration leading to increased site wetness (Dubé and Plamondon, 1995) or by releasing the ericad species from competition (Weetman et al., 1990; Titus et al., 1995). In summary, the consequences of forest management on soil biological properties and their link to productivity are clearly open questions.

7. Fire

Fire has been mentioned in this review. Extensive forest management most often includes protection from fire, but can include use of fire as a silvicultural tool and as a tool of ecosystem management (Arno, 1996). Both exclusion and inclusion of fire have effects on soil properties and hence on productivity. The effects of fire on soils have been the topic of many studies, and a thorough review would easily double the size of this review. Many such fire reviews are available (Ahlgren and Ahlgren, 1960; Wells et al., 1979; Woodmansee and Wallach, 1981; MacLean et al., 1983; DeBano, 1990; Raison et al., 1990), and that information will not be repeated here. There are, however, some general points that can briefly be made.

Before the arrival of Europeans, fire was a common ecosystem disturbance in many North American forests, and although less common it remains a frequent disturbance in many mountainous and boreal systems. It could be argued that soils have developed with periodic fires, and fire therefore should not be considered to be deleterious. Disruption of the more normal fire cycle by suppression has led to fires of greater intensity, albeit lower frequency, than in pre-European time. Such high intensities can lead to surface erosion and mass flow, to nutrient loss via volatilization and post-fire leaching, and to significant changes in the soil biota. Conversely, fires can also lead to increased availability of nutrients and increased site productivity. It is clear that consequences of fire on soil properties and their link to productivity are open questions (e.g., Johnson et al., 1998).

8. Evaluation

8.1. Relative importance

My qualitative evaluation of the significance of effects of extensive forest management on productivity indicates an overwhelming importance of alterations of soil physical properties (Table 1). Physical properties are easily altered, and those alterations are of relatively long duration, of high certainty, are not easily repaired, represent deviations from the natural range of conditions, and have significant and well-documented negative effects on productivity. Conversely, except on a few exceptional sites, nutrient loss is not a major concern. Its effects are not well-documented and appear to be long-term. Even in situations where it is a potential concern, measurable effects are

Table 1
Assessment of effects of extensive forest management activities on soil properties and thence on soil productivity and sustainability

Effect	Severity	Spatial extent	Certainty	Duration	Deviation from natural	Implications	Importance
Surface erosion	Low	Large	Medium	Medium	No	Water quality	Medium
Mass flow	High	Small	Low	Long	Yes	Water quality	Medium
Roads	High	Medium	High	Long	Yes	Access for management	High
Compaction/rutting	Medium	Medium	High	Medium to long	Yes		Medium
Site disturbance	Medium	Large	High	Medium	Yes	Collective measure	High
Nutrient loss by leaching	Low	Large	Medium	Short	No		Low
Nutrients loss in product	Medium	Large	High	Medium to long	Yes		Low
Biological disruption	Medium	Large	Medium	Medium	No		Low

likely to require more than one rotation to occur. This provides time to more fully investigate both the reality of the concern and potential ameliorative measures.

Many of the data reviewed here indicate that on sites with moderate disturbance, decreases in productivity in the range of 10% can occur because of alteration of soil physical properties. Combined with the reduction in the land base due to infrastructure such as roads and landings (an additional ca. 10%), there can be a substantial change in stand-level productivity over one rotation. An *increase* in productivity of that magnitude would be cause for celebration. This alteration is more immediately significant and more likely than modeled changes (uncertain) associated with global change (also uncertain). It is ironic that as our knowledge and technology increase, our ability to damage our basic resource also increases.

8.2. Recommendations

8.2.1. Scale of assessment

Most of the effects of forest management that I have discussed are site-specific, stand level. Concern should really be directed at the landscape scale, at the aggregation of sites. There are at least two reasons for recommending the landscape perspective when evaluating effects of extensive management:

1. Some landscapes are more sensitive to a specific effect than are others. For example, landscapes with shallow, coarse-textured, low nutrient soils are most susceptible to nutrient depletion; steeply sloping landscapes with loamy soils are susceptible to surface erosion; specific bedrock landforms in mountainous areas are susceptible to mass flow.
2. Meaningful evaluation of the effects on productivity should be integrated; the summation of growth alteration per unit area of landscape. Within landscapes and even within sites there is great variability in sensitivity and in effects. For example, within a site the primary skid trails may become heavily compacted while at lower-lying portions of a landscape they may become rutted. Each change will have its own unique effect on productivity. The cumulative effect is most important to an assessment; an effect may be severe at a local scale but may be minor over a landscape.

The landscape level should be used to both understand the effects of forest management on productivity and to minimize or ameliorate the effects. Appropriate landscape classification schemes have great potential to help communicate concerns and solutions to the general public and to the multiplicity of owners.

8.2.2. Minimization techniques

If extensive forest management implies minimal monetary investment, what can be done to minimize negative effects or ameliorate affected areas? First, we cannot control weather and site factors such as slope characteristics, rainfall intensity, or soil texture, and because of other considerations (e.g., economic) it is likely that we have only minimal control over timing of stand entries, either seasonally in thinning or in harvest schedules. Yet extreme care should be taken to minimize alteration of soil properties. Because so few important causal factors can be controlled, it becomes clear that the major technique for minimization of negative effects of extensive management is simply *planning*. Those who most frequently come in contact with areas under extensive management, both foresters and loggers, should be made aware of the negative effects of forest harvest while simultaneously being able to use the harvest as a silvicultural tool. Professional accountability, although implicit in the forestry profession, is becoming a legal mandate in many jurisdictions in part because of the perception of continuing inattention to some of these issues. If forestry has a goal of sustainability, that phrase implies revisiting the stand; harvesting it again. If many of the impacts of forest management are unavoidable and irreversible either because of physical principles or monetary considerations, then we should minimize the area that is affected. The infrastructure for stand access should be minimized, including both major roads and landings and also primary and even secondary skid trails. We should concentrate effects, not spread them throughout the harvest area. There are both techniques and equipment that may help minimize the negative effects of stand entries, and they are elaborated in many management guidelines (e.g., Lewis, 1991; Grigal and Bates, 1992; Archibald et al., 1997). Unfortunately, because of their cost most ameliorative activities fall outside the scope of extensive forestry. In the context of extensive forestry, the major ameliorative measure is time.

9. Conclusions

Forest management activities are necessary parts of forestry, and we may have minimal control over the circumstances under which they are carried out. Alterations of soil physical properties are extensive, immediate, and their effects in reducing productivity are well-documented. Soil chemical and biological properties are also changed by management activities, but the effects on productivity are less well-documented and of longer term; their influence is not clear. Historical evidence shows that forest ecosystems are dynamic and resilient. Assessment of the consequences of changes in properties must recognize that shifts in preferred species should not be equated with changes in productivity, and that short-term effects, measured by the length of most experiments or observations, may not be indicative of long-term effects. As discussed earlier, this review has focused on soil productivity as one part or element that significantly affects forest productivity. Accurate assessment of the effects of its change, however, is likely to continue to be obscured by the influence of the many other elements that also affect forest productivity (Weetman, 1998). At our current state of ignorance, a reasonable approach may be a simple sensitivity analysis that uses spatially based techniques (geographic information systems) and reasonable estimates of the effects of the many factors that affect forest productivity to develop an impression of the importance of changes in soil productivity. Use of more sophisticated simulation models implies greater knowledge than we currently possess. Both ethical and economic considerations demand good stewardship with professional accountability for our natural resources. Extensive forest management, if carried out with both wisdom and prudence, is not antithetical to good stewardship. "All of us have vested interests in making forest management a wise and efficient use of resources. Soil information can immeasurably help us be good stewards of the land" (Grigal, 1984).

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